Trace Gas Transport in the Arctic Vortex inferred from ATMOS ATLAS-2 Observations during April 1993

M. C. Abrams[1], G. L. Manney[2], M. R. Gunson[2], M. M. Abbas[3], A. Y. Chang[2], A. Goldman[4], F. W. Irion[5,2], H. A. Michelsen[6], M. J. Newchurch[7], C. P. Rinsland[8], R. J. Salawitch[2], G. P. Stiller[9], and R. Zander[10]

Abstract. Measurements of' the long-lived tracers CH_4, N_2O and HF from the Atmospheric Trace Molecule Spectroscopy (ATMOS) instrument during the Atmospheric Laboratory for Science and Applications-2 (ATLAS-2) Space Shuttle mission in April 1993 arc used to infer average winter descent rates ranging from 0.8 km/month at 20 km to 3.2 km/month at 40 km in the Arctic polar vortex during the 1992-93 winter. Descent rates in the mid-stratosphere arc similar to those deduced for the Antarctic vortex using ATMOS/ATLAS-3 measurements in November 1994, but the shorter time period of descent in the Arctic leads to smaller total distances of descent. Strong horizontal gradients observed along the vortex edge indicate that the Arctic vortex remains a significant barrier to transport at least until mid-April in the lower to middle stratosphere.

introduction

Recent theoretical studies have addressed the transport of air through the polar vortices and the evidence for and against the mixing of air confined within the vortex with extra-vortex air. *Manney et al.*, [1994a] simulated the three-dimensional motion of air through the polar vortices using horizontal winds from the United Kingdom Meteorological Office (UKMO) data assimilation system [*Swinbank and O'Neill, 1994]* and vertical velocities from a radiation calculation. *Rosenfield et al., [1994]* combined a radiation model with National Meteorological C.enter (NMC) temperature observations to compute heating rates and descent rates for long-lived tracers in the Northern hemisphere and Southern hemisphere winter vortices, *Schoeberl et al.*, [1995] obtained descent rates within the lower stratosphere in the southern hemisphere (SH) from HALOE observations, and *Manney et al. [1995]* calculated descent rates in the lower stratosphere in both the northern hemisphere (Nil) and SH.

The third flight of the ATMOS instrument as part of the ATLAS-2 Shuttle mission captured a unique view of the late winter state of the Arctic stratosphere in April 1993 by recording solar occultation measurements inside and outside the polar vortex. The observed distributions of the long-lived tracers N_2O, CH_4, and HF give information on transport effects that have occurred during the winter, and provide a dynamical context for analyses of the chemistry of reactive nitrogen and chlorine species as the polar vortex erodes in spring. Approximately 50 sunrise observations were concentrated in a narrow band of latitudes from 60-65° N, with the remaining sunset observations latitudes between the Equator and 50° S. The ATLAS-3 mission, flown eighteen months later in November 1994, provided measurements at high Northern midlatitudes, from which the seasonal variation in the upper stratospheric trace gases can be addressed. The results presented in this Letter focus on estimation of descent rates from profiles of N_2O, CH_4, and HF measured inside and outside the Arctic polar vortex during late winter and complement an analysis of similar measurements presented in an accompanying Letter [*Abrams et al.,* 1996] of descent within the Antarctic polar vortex.

Mean tracer **profiles and descent rates**

Fig. 1 shows a cross-section of N_2O as a function of longitude and potential temperature (θ), constructed from data taken throughout the nine day ATLAS-2 mission. Two regions of very strong gradients in N_2O are seen between 50^0 and 150^0 E longitude, at levels up to about 900 K (approx. 30 km), indicating that vortex and extra-vortex air remain largely unmixed in the lower and middle stratosphere as late as mid-April 1993. As was the case in the S11 [*Abrams et al.,* 1996], contours of scaled potential vorticity (sPV) [*Manney et al.,* 1994], overlaid in Fig. 1, show large gradients coincident with the steep N_2O gradients, although the sPV gradients extend up to about 1200 K. The existence of strong N_2O gradients along the vortex edge in the middle and lower stratosphere supports the theoretical calculations of *Manney et al. [1994],* who showed confinement of air in the lower to middle stratospheric vortex in early April 1993. Similar features arc apparent in cross-sections of ATMOS measurements of CH_4 and HF (not shown).

As in *Abrams et al. [1996],* we construct average vortex and extra-vortex profiles of N_2O, CH_4 and HF on the basis of both tracer mixing ratios and sPV values on the 655 K isentropic surface. Profiles with N_2O and CH_4 less (greater) than 30 ppbV and 0.6 ppmV, respectively, and sPV greater (less) than 1.6 (1.2) arc considered to be inside (outside) the vortex. Figs. 2-4 show the mean vortex and extra-vortex profiles of N_2O, CH_4 and HF determined in this manner. As was apparent in Fig. 1, there is a strong distinction between vortex (low N_2O, low CH_4, high HF) and extra-vortex (high N_2O, high CH_4, low HF) profiles at levels below about 35-40 km. Below 20 km, vortex and extra-vortex profiles begin to converge, suggesting that them may be a larger degree of horizontal mixing below this level.

Profiles of tracers obtained in the ATLAS-3 mission at Northern mid-latitudes (46° N) in late fall (3-12 November 1994), shown in Figs. 2-4, provide a measure of seasonal variation in the mid-latitude upper stratosphere. These observations suggest some seasonal variation above about 35 km. Between 25 and 35 km, the vortex profiles of N_2O and CH_4 show a secondary maximum and HF a secondary minimum; above this, they closely resemble the extra-vortex profiles. This is evidence that there is no longer any significant barrier to horizontal transport in the upper stratosphere, since vortex and extra-vortex air arc no longer distinguishable. 1 lowever, despite the large amount of dynamical activity that has occurred throughout the winter [e.g., *Manney et al., 1994]*, at levels below about 30 km there is a distinct separation between the spring vortex and extra-vortex tracer mixing ratios. At these levels, a signature of relatively unmixed descent in the vortex is apparent. Mixing ratios in the lower stratospheric vortex (e.g., 20 km) arc typical of middle to upper stratosphere extra-vortex values (e.g., 35-40 km). The lack of evidence of mesospheric air in the Arctic vortex, as was seen in the Antarctic during November 1994 [*Abrams et al.*, 1996], is probably duc primarily to the shorter period of descent and the greater degree of horizontal mixing in the Arctic,

Descent rates arc inferred from the tracer measurements by estimating the vertical separation between the late winter vortex and extra-vortex tracer profiles for similar tracer mixing ratios, as discussed in greater detail by *Abrams et al. [1996]*. The estimates of descent rates depend upon an assumption of unmixed descent (that is, the only thing that alters the profiles is vertical motion); while this assumption has been shown to be less appropriate in the NH than in the S11, the strong tracer gradients along the vortex edge below about 30 km suggest that it is a valid assumption at these levels. Differences between the extra-vortex spring profile and the winter midlatitude profile suggest some seasonal differences in the midlatitude upper stratosphere. in addition, the 'vortex' profile is similar to the 'extra-vortex' profile at these levels, since the vortex has broken down, and mixing occurred, as discussed above. Thus, any signature of unmixed descent at levels above about 35 km has been obscured by mixing.

Rosenfield et al. [1994] assumed a starting date of 1 Nov. for NH descent rate calculations, and a 4.6 month period of descent ending on 21 March. As discussed by *Abrams et al. [1996]*, the most appropriate starting date for calculations of unmixed descent is a function of altitude, and depends on when a barrier to transport has formed at the appropriate level. Table 1 shows two descent rates: the first calculated assuming a 1 Nov. starting date (Rate), and the second assuming an adjusted starting date based on examination of sPV gradients (Adj. Rate, assuming the starting date (St, Date) given in tbc table), as described by *Abrams et al.* [1996]. Fig. 5 shows descent rates calculated using tbc adjusted starting dates and observations of N_2O, CH_4, and HF. These arc compared with several previous theoretical results. The results for each of the three tracers measured by ATMOS arc consistent within the measurement precision. The results agree favorably with theoretical descent rates for tbc NH obtained by *Manney et al.* [1994] and *Rosenfield et al.* [1994] in the middle stratosphere between 30 and 35 km, but below 30 km the theoretical results arc 60% larger than the measurements at 25 km and 100% larger than the measurements at 20 km. Recalling that the tracer profiles suggested more mixing near 20 km, the calculations from ATMOS measurements may underestimate descent at low altitudes because tbc profiles arc significantly affected by horizontal transport. in tbc upper stratosphere, there is no evidence of large scale descent of air, as suggested by the theoretical calculations [*Rosenfield et al., 1994; Manney et a/., 1994]*, or of air originating above the stratopause, as was apparent in the Antarctic [*Abrams et al.,* 1996]. However, during the ATLAS-2 mission, horizontal mixing is expected to dilute the vortex air sufficiently at these altitudes so as to obscure any evidence of vertical motion. The absence of extremely low N_2O and CH_4 mixing ratios such as those observed in the Antarctic lower stratosphere may be explained by the shorter duration of the period of descent, and tbc mixing that has already occurred in the Arctic upper stratosphere.

Previous analyses of descent in the Arctic used onc of three classes of long-lived tracer measurements: airborne column or *in situ* measurement which provide spatially distributed results without vertical information, or balloon-borne measurements which yield information about the vertical distribution of tracers, but only at a specific location. *Mankin et al. [1990], Toon et al. [1992],* and *Traub et al., [1994]* inferred 5-6 km of subsidence within the polar vortex from total column measurements obtained onboard the NASA DC-8 aircraft. Similarly, *Lowenstein et al.* [1990] inferred a subsidence of 4-6 km above 17 km based on measurements from tbc NASA ER-2 aircraft. Balloon measurements between 1987 and 1990 at 68° N suggested a vertical subsidence of about 7 km over tbc period bet wccn November and February [*Schmidt et al., 1991]. To* the degree possible without detailed vertical information inside and outside the polar vortex, these measurements arc consistent with tbc measurements from the ATLAS-2 mission as well as model calculations. Descent rates have been inferred in several more recent experiments: *Bauer et* al. [1994] obtained vertical descent rates of 2.0 km/month at 29.8 km, which agrees adequately with tbc present measurements, but also found rates of 3.1 km/month around 26 km which is nearly a factor of two larger than ATMOS measurements and theoretical estimates. *Schoeberl et al. [1992]* and *Traub et al. [1995]* obtained descent rates of 1.29 and 1.30 km/month in the lower stratosphere at 15.5 and 18 km, respectively. The disagreement between the ATMOS/ATLAS-2 measurements and the theoretical results (supported by the measurements of *Traub et al.* [1995] and *Schoeberl et al. [1992]*) may result from differences between the years of the observations (1992 and 1990, respectively), the lack of vertical resolution, different assumptions about the descent period, or from the ATMOS observations underestimating descent once horizontal mixing becomes significant. The inclusion of measurements at the 'edge' of the polar vortex which arc likely to be most affected by mixing would lead to an underestimation of the descent rates, however, the statistical weight of such measurements was assessed and determined to be small relative to the measurement variance. The extra-vortex seasonal variation, illustrated in Figs. 2-4 is no more that 2 km at most altitudes and would, results in a modest increase in the dm.cent rates. Similarly, the estimation of 'net' descent rates neglects the detailed motion of the air during the winter and consequently may overestimate the descent period. Manney et al [1995] use results from CLAES to deduce descents rates of-1.4 and 1.6 km/month during the 1992-93 early and late winter, respectively, at about 21 km, falling *near* the theoretical values, but between those and the estimates from ATMOS observations. in comparison with the analysis of descent from ATMOS observations within the Antarctic polar vortex [*Abrams et* al., 1996], the average descent rates in the Arctic arc similar to those calculated for the Antarctic. However, because of the shorter period of descent in the Arctic, the magnitude of the total descent in the Arctic is much less.

Conclusions

I'race gas measurements made by the ATMOS instrument as part of the ATLAS-2 and 3 Space Shuttle missions arc used to infer descent rates in the Arctic polar vortex for the 1992-3 winter. The results compare favorably with the theoretical calculations of *Manney et al. [1994a]* and *Rosenfield et al. [1994]* in the mid-stratosphere and provide more information about the vertical extent of air motion and descent rates than previously available. Comparison to a similar analysis of ATMOS measurements in the Antarctic vortex shows similar descent rates in both hemispheres, but much deeper total descent in the Antarctic due to the longer period over which descent occurs, The ATMOS observations of N_2O, CH_4 and HF in the Arctic indicate that, despite the erosion of the vortex that has already occurred in the upper stratosphere, a clear separation between vortex and extra-vortex air persists until mid-April 1993 in the middle and lower stratosphere. Future work will apply these descent rates to reactive species with the intention of characterizing the dynamical component present in ATMOS measurements of O_3, HCl, and CO.

Acknowledgments. Research at the Jet Propulsion Laboratory (JPL), California Institute of Technology, is performed under contract to the National Aeronautics and Space Administration (NASA). Research at the University of Liège was partially supported by the Belgian Global Change Program through the SSTC, Brussels.

References

Abrams, M. C., *et al.*, ATMOS/ATLAS-3 Observations of trace gas transport in the Antarctic vortex in November 1994, *Geophys. Res. Lett.*, this issue, 1996.

Bauer, R. A., et *al.*, Monitoring the vertical structure of the Arctic polar vortex over northern Scandinavia during EASOE: regular N_2O profile observations, *Geophys. Res. Lett.*, *21*, 1211-1214, 1994.

Lowenstein, M., J. R. Podolske, K. R. Chan, and S. E. Strahan, N_2O as a dynamical tracer in the Arctic vortex, *Geophys. Res. Lett.*, *17*, 477-480, 1990.

Mankin, W. G., M. T. Coffey, A. Goldman, M. R. Schoeberl, L. R. Lait, and P. A. Newman, Airborne measurements of stratospheric constituents over the Arctic in the winter of 1989, *Geophys. Res. Lett.*, 17, 473-476, 1990.

Manney, G. L., R. W. Zurek, A. O'Neill, and R. Swinbank, On the motion of air through the stratospheric polar vortex, *J. Atmos. Sci.*, 51, 2973- 2994, 1994a..

Manney, G. L., ct al., Langrangian transport calculations using UARS data. part 1: Passive tracers, *J. Atmos. Sci.*, 52, 3049-3068, 1995.

Rosenfield, J. E., P. A. Newman, and M. R. Schoeberl, computations of diabatic descent in the stratospheric polar vortex, *J. Geophys. Res.*, 99, 16677-16689, 1994.

Schmidt, U., R. Bauer, A. Khedim, E. Klein, G. Kulessa, and C. Schiller, Profile observations of long-lived trace gases in the Arctic vortex, *Geophys. Res. Lett.*, 18, 767- 770, 1991.

Schoeberl, M. R., L. R. Lait, P. A. Newman, and J. E. Rosenfield, The structure of the polar vortex, *J. Geophys. Res.*, 97, 7859-7882, 1992.

Schoeberl, M. R., L. Mingzhao, and J. E. Rosenfield, An analysis of the Antarctic Halogen Occultation Experiment trace gas observations, *J. Geophys. Res.*, *100*, 51 S9-S 172, 1995.

Swinbank, R, and A. O'Neill, A stratospbcrc-troposphere data assimilation system, *Mon Weather, Rev.*, *122*, 686-702, 1994.

Toon, G. C., C. B. Farmer, P. W. Schaper, L. L. Lowes, R. }1. Norton, M. R. Schoeberl, L. R. Lait, and P. A. Newman, Evidence for subsidence in the 1989 Arctic winter stratosphere from airborne infrared composition measurements, *J. Geophys. Res.*, 97, 7963-7970, 1992.

Traub, , W. A., K. W. Jucks, D. G. Johnson, K. V. Chance, Chemical change in the Arctic vortex during AASE II, *Geophys. Res. Lett.*, 21, 2S95-2598, 1994.

Traub, W. A., K. W. Jucks, D. G. Johnson, K. V. Chance, Subsidence of the Arctic stratosphere determined from thermal emission of hydrogen fluoride, *J. Geophys. Res.*, 100, 11261-11267. 1995.

M. C. Abram (m.c.abrams@larc.nasa.gov), NASA LaRC MS-475, lampton, VA, 23681, USA

Author Addresses:

1 SAIC - NASA Langlcy Research Centcr

2 Jet Propulsion Laboratory

3 NASA Marshall Space Flight Centcr

4 Univcrsit y of Denver

5 California Institutc of Tcchnology

6 Harvard Univcrsity

7 University of Alabama at Huntsvillc

8 NASA Langley Research Centcr

9 Forschungszcntrum Karlsruhc

10 Institutc of Astrophysics, University of Liege

Figure Captions:

Figure 1. Potential tcmpcraturc-longitude cross-section at 62 N of $N_2$0 (color) and sPV (contours). The region of the vortex is clearly defined by the steep gradients in potential vorticity bctwccn 1.2 and 1.6 in the lower stratosphere bctwccn 40° and 150° longitude.

Figure 2. Mean $N_2$0 volumc mixing ratio profiles for 'inside' and 'outside' the Antarctic polar vortex and a midlatitudc zonal mean profile (46N) obtained during the ATLAS-3 mission (1 1/94) which indicates tbc minimal seasonal variation outside the vortex at midlatitudcs. Descent rates will bc inferred from the vcrtical separation bctwccn the mean late winter vortex and extra-vortex tracer profilcs.

Figure 3. Mean CH_4 volume mixing ratio profiles,

Figure 4. Mean HF volume mixing ratio profiles.

Figure S. Descent rates obtained from ATMOS trace gas measurements compared with theoretical predictions.

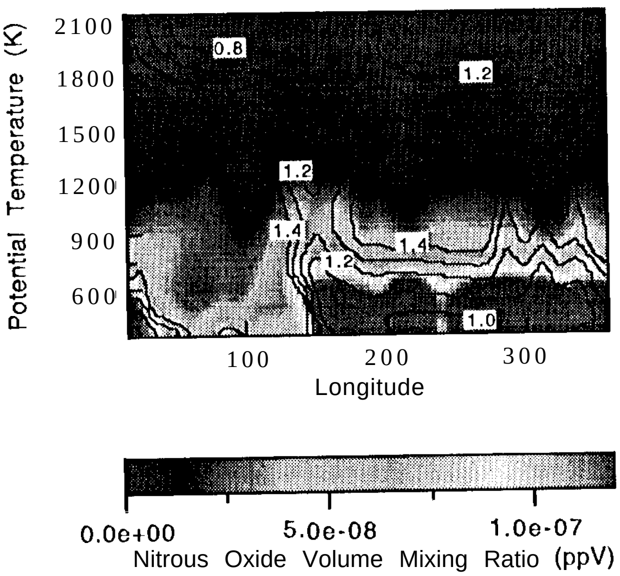


Figure 1.

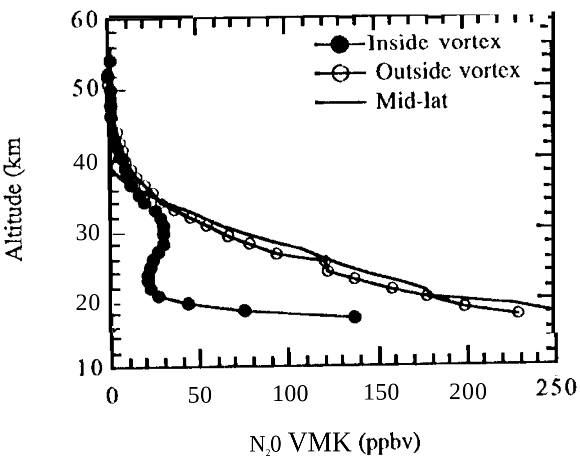
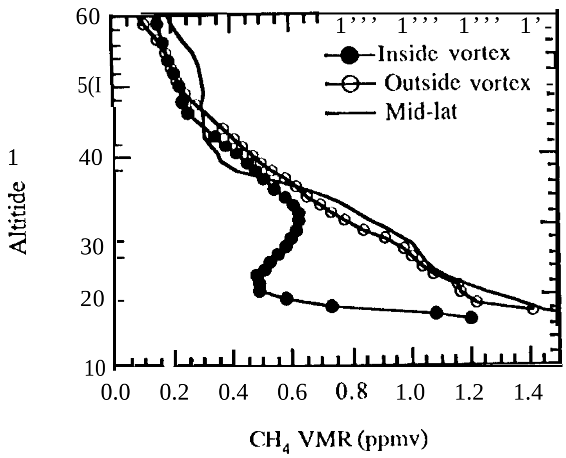


Figure 2.



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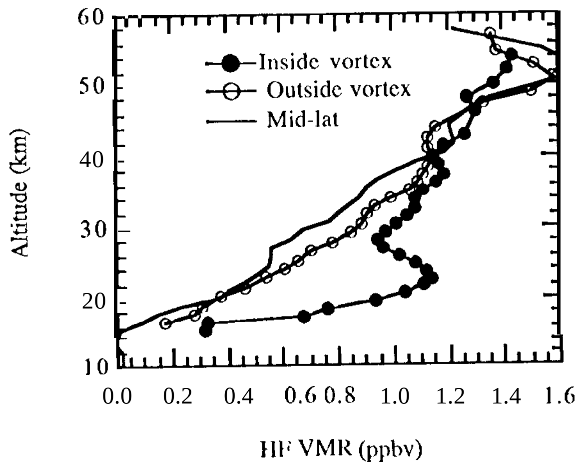

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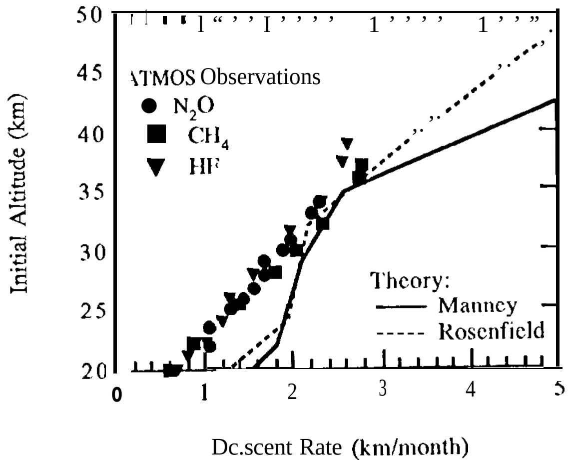

Figure 5.

Table 1: ATMOS/ATLAS-2 Net Arctic Descent Rates

St.Alt. (km)	St. Θ (K)	Delta (km)	Rate (km/mo)	St. Date (dd/mm)	Adj. Rate (km/mo)
50	1700		---	1 Ott	---
42	1300		---	1 Ott	---
34	960	13.8	2.6	15 Ott	2.4
30	840	11.1	2.2	20 Ott	1.9
24	655	6.4	1.2	1 Nov	1.2
20	520	3.7	0.7	10 Nov	0.74
17	465		---	12 Ncrv	—
15	425		---	*	---

* at this level the starting date is uncertain, but much later than for the other levels.